Precision Study of MSSM at future e^+e^- linear colliders

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The lighter scalar tau lepton $\tilde{\tau}_1$ may be the lightest scalar lepton and therefore would be found earlier in future collider experiments. We point out the impact of the measurement of the mass and the mixing angle of $\tilde{\tau}$ to discriminate the models of SUSY breaking. Furthermore, the measurement of the polarization of τ lepton(P_τ) from the decaying $\tilde{\tau}_1$ helps to determine the Yukawa sector of minimal supersymmetric standard model. We present our MC study of the production and the decay of $\tilde{\tau}_1$ lepton at a future linear collider at $\sqrt{s} = 500$ GeV. The mass, mixing angle of $\tilde{\tau}_1$ and $P_\tau(\tilde{\tau}_1 \to \tau\chi^0_1)$ would be measured precisely at the future LC.

§1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) [1] is one of the most promising candidates of the models beyond the Standard Model (SM). It predicts the existence of superpartners of SM particles below a few TeV to remove quadratic divergence which appears in radiative corrections of the SM Higgs sector; thus the model is free from the so–called hierarchy problem of GUT models. It should be noted that the gauge couplings unify very precisely at high energy scale in MSSM,SUSY SU(5) GUT predictions.

The supersymmetry is not an exact symmetry of the model, instead it should be somehow broken to give the mass differences between a particle and its superpartner. Various attempts have been made to explain the existence of the soft SUSY breaking [2,3]. Those different models of SUSY breaking have different predictions for the relation between the soft breaking mass parameters at some high scale M_{SB}; m_i (scalar masses), M_i(gaugino masses), A_i(trilinear couplings) and B(Higgsino soft breaking mass parameter). Evolving the mass parameters by the RGE of the model from M_{SB} to $M_{\rm weak}$, one gets the prediction of the mass spectrum of superpartners at the weak scale.

Therefore, the precise measurement of masses and interactions of superpartners will be one of the most important physics targets once they are discovered. This might enable us to discriminate the models of even higher energy scale responsible for the SUSY breaking if the experiment reaches certain sensitivity. Notice that to claim a new particle as a superpartner also requires careful investigations of the interaction of the particle which should agree with the expectations of supersymmetry.

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Proposed Linear Colliders at $\sqrt{s} = 500$ GeV are expected to have high luminosity— $\mathcal{L} = 30 fb^{-1}/\text{year}$ [4), 5)]. The background from W boson production can be suppressed drastically thanks to the highly polarized electron beam; Current technology already archived $P_{e^-} = 80\%$ at SLC, and $P_{e^-} = 95\%$ is proposed at future LC's. Under this clean environment, precision study of the mass and interaction become possible. Studies of accelerator technology for the future LC's are on going in several institutes such as SLAC, KEK, DESY and CERN. [5)]

The potential impact of a LC to the supersymmetric models have been pointed out by several groups already [6), 7)]. For example, the predictions of the Minimal Supergravity(MSUGRA) model for M_1/M_2 and $m_{\tilde{e}}/\ m_{\tilde{\mu}}$ have been shown to be proven up to $\mathcal{O}(1\% \sim 10\%)$. Ino-lepton-slepton coupling also can be measured to check the prediction of supersymmetry. Those analyses have been done for $\tilde{e}, \tilde{\mu}$ and $\tilde{\chi}^+$ pair production modes.

In the following, I will talk about our MC study of the production and decay of $\tilde{\tau}$ at a future LC [8), 9)]. The decay of $\tilde{\tau}$ involves a τ lepton, which decays further in the detector. It makes analysis rather complicated, and therefor MC study of the process have not been done previously. However, the physics coming out from the study turns out to be fruitful, due to the unique nature of $\tilde{\tau}$ interaction through Planck scale to the weak scale.

In Sec. 2.1, we briefly describe the reduction of $m_{\tilde{\tau}_{L,R}}$ by the GUT scale Yukawa interaction in MSUGRA-GUT model, which has been pointed out recently by Barbieri and Hall [10)]. $\tilde{\tau}$ would be found earlier than the other SUSY particles in the model as the $\tilde{\tau}$ mass is expected to be much lighter than other sleptons. It is also stressed measurement of $m_{\tilde{\tau}_{L,R}}$ provides clear cuts to distinguish the MSUGRA-GUT from other models.

Blow the GUT scale, the interaction of τ lepton is still different to the other sleptons as it has a non-negligible Yukawa coupling $Y_\tau \propto m_\tau/\cos\beta$; Here $\tan\beta$ is the ratio of vacuum expectation values of the two neutral Higgs boson in MSSM. The Yukawa coupling is enhanced linearly $\propto \tan\beta$ for large value of $\tan\beta$. A consequence of the large Yukawa coupling is existence of left-right mixing of $\tilde{\tau}$; The lighter mass eigenstate of $\tilde{\tau}$ would be lighter than the other sleptons even if mass parameter of $\tilde{\tau}$ is equal to that of $\tilde{e}$ and $\tilde{\mu}$. The feasibility of determination of the mass and mixing angle at a future LC is checked by MC simulation in Sec. 2.2.

The same Y_τ appears as a non-negligible $\tau\tilde{\tau}\tilde{H}_1^0$ coupling, where $\tilde{H}_1^0$ is a neutral higgsino. The ratio of the couplings involving higgsino component and gaugino component of neutralino χ^0, where the neutralino is a mixture of higgsinos and gauginos, can be determined through the measurement of the polarization of τ lepton(P_τ) from $\tilde{\tau}$ decay into a neutralino and τ. The strong sensitivity of P_τ to $\tan\beta$ helps to determine $\tan\beta$, by combining the information from the other modes. The performance of LC experiment on the determination of P_τ will be found in Sec. 2.3. Sec. 3 is devoted for conclusion and discussions.

§2. Study of Scalar Tau Lepton at LC

2.1. *Mass of Scalar Tau and Models of Supersymmetry breaking*

$\tilde{\tau}_{L(R)}$ is the superpartner of $\tau_{L(R)}$, the third generation lepton. This makes $\tilde{\tau}$ an unique object in the context of the SUGRA-GUT model [2)]. In the supergravity model, the SUSY breaking in the hidden sector gives the soft breaking mass through gravitational interaction at Planck scale M_{pl}. The resulting scalar mass is universal at M_{pl}, leading to approximate universality of $m_{l_{L,(R)}}$ if their interaction is equal from M_{pl} to $M_{\rm weak}$. However, in simple grand unified models such as SO(10) or SU(5), the τ superfield is in the same multiplet with the top quark superfield above the GUT scale M_{GUT}. Thus from M_{pl} to M_{GUT}, the τ supermultiplet obeys the same Yukawa interaction as that of top quark. The large top Yukawa interaction is anticipated by the top mass measurement by CDF or D0 [11)], and this reduces the masses of $\tilde{\tau}_R$ (or $\tilde{\tau}_{L(R)}$) at M_{GUT} compared to its value at M_{pl} for SU(5) (or SO(10)) GUT model. This is pointe out in Ref.10) and they claimed that $m_{\tilde{\tau}}$ can be as light as a half of $m_{\tilde{e}}$. $m_{\tilde{\tau}}$ may even be the second lightest SUSY particle in this model.

I should stress that there exists a model which predicts totally different mass spectrum. Dine-Nelson-Nir-Shirman [3)] recently constructed relatively simple models which break SUSY at an intermediate scale [$\sim 10^{6\sim 7}$ GeV] dynamically(DNNS model). The breaking is then transformed to our sector by $U(1)$ gauge interaction, which is called a messenger sector. The scale where the gauge interaction breaks(M_m) is $O(10^4)$ GeV. Due to the nature of the gauge interaction, the resulting scalar masses of sleptons are common for (l_L, ν_l) and l_R at M_m respectively. Unlike SUGRA-GUT model, they remain roughly equal at M_{weak}, as M_m is considerably close to M_{weak} and there is no strong Yukawa interaction involved between the scales. Therefore, determination of $m_{\tilde{\tau}_{L,R}}$ would give us a good handle to distinguish the scale of SUSY breaking below or above the GUT scale.

2.2. *Determination of $\tilde{\tau}$ mass matrix at LC*

To determine $m_{\tilde{\tau}_{L,R}}$, one has to know $\tilde{\tau}$ interaction. This is because neither $\tilde{\tau}_L$ nor $\tilde{\tau}_R$ is a mass eigenstate, but they generally mix to make the mass eigenstates $\tilde{\tau}_{1(2)}$; The mass matrix is expressed as

$$\mathcal{M}^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^2_{LR} & m^2_{RR} \end{pmatrix} = \begin{pmatrix} m^2_L + m^2_\tau + 0.27D & -m_\tau(A_\tau + \mu\tan\beta) \\ -m_\tau(A_\tau + \mu\tan\beta) & m^2_R + m^2_\tau + 0.23D \end{pmatrix}, \tag{1a}$$

and the mass eigenstates are expressed as

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}. \tag{1b}$$

Here μ is Higgsino mass parameter, $\tan\beta \equiv \langle H^0_1\rangle/\langle H^0_2\rangle$ is the ratio of vacuum expectation values, and A_τ is the coefficient of the soft breaking term proportional to τ_R-τ_L-H_1, and D corresponds to D-term.

The mixing makes the lighter mass eigenvalue $m_{\tilde{\tau}_1}$ lighter than diagonal mass terms, thus even in the model with the common soft breaking scaler mass, $m_{\tilde{\tau}_1}$ may be lighter than $m_{\tilde{e}}$ [12)]. At the same time, one has to know θ_τ together with $m_{\tilde{\tau}_1}$ and

$m_{\tilde{\tau}_2}$ to determine $m_{\tilde{\tau}_L}$ and $m_{\tilde{\tau}_R}$. Notice that it is interesting to observe the non-zero θ_τ(mod π) as this proves the existence of the off-diagonal element of the $\tilde{\tau}_1$ mass matrix; this depends on the term proportional to $\mu \cdot \tan\beta$ which is required from supersymmetry, while A_τ is the coefficient of the trilinear soft breaking term. Both terms are strongly motivated by the supersymmetric theory.

If the electron beam is polarized, the mixing angle θ_τ will be determined from the measurement of the production cross section $e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$ [8]. This can be easily explained by taking the limit where $m_Z \ll \sqrt{s}$ and $P_e = 1$. In the limit, the production of $\tilde{\tau}$ solely proceed through $U(1)$ gauge interaction that carries hypercharge. The hypercharge is $-1/2(-1)$ for $\tilde{\tau}_{L(R)}$, thus $\sigma(\tilde{\tau}_R) \sim 4\sigma(\tilde{\tau}_L)$. The cross section also depends of $m_{\tilde{\tau}_1}$, however this would be extracted from the energy distribution of $\tilde{\tau}$ decay products, as we will see later.

To show the feasibility of the measurement of $m_{\tilde{\tau}_1}$ and θ_τ at a future e^+e^- collider, we did MC simulation for the JLC1 detector [4]. We took $\sqrt{s} = 500$ GeV and $P_e = 95\%$, and analysed the process where $\tilde{\tau}_1$ decays into $\chi_1^0\tau$ exclusively; here χ_1^0 is the lightest neutralino and we assumed χ_1^0 to be the lightest SUSY particle and stable, and we denote it by χ hereafter .

Due to the simple 2 body kinematics, the energy distribution of τ leptons is flat between E_{min} to E_{max} , which contains the information about m_χ and $m_{\tilde{\tau}_1}$. Actually for the process $e^+e^- \to \tilde{e}^+\tilde{e}^-$ and $\tilde{e} \to \chi e$, the energy distribution of the electrons was used to determine $m_{\tilde{e}}$ and m_χ [6]. However the τ lepton decays further into π, ρ, a_1, e and μ etc.. The decay distribution depends not only on the $E_{max(min)}$ but also on the decay modes of τ lepton.we reconstructed ρ and a_1 whenever it is possible.[*)]

We require both of the τ decays hadronically as signal to avoid relatively large background from eeZ^0 and $e\nu W$. We also include backgrounds from W^+W^-, Z^0Z^0, $e^+e^-W^+W^-$ and $\nu\nu Z^0$ productions. Cuts like $E_{vis} > 10$ GeV and $\theta_{accop} > 30°$ are applied to reduce the backgrounds too. The resulting signal of τ production is characterized as 2 jets of low hadron multiplicity with missing P_T. Those selected MC samples are then used to 'measure' m_χ and $m_{\tilde{\tau}_1}$ by fitting the energy distribution of the MC sample.

In figure 1, we show the results of the mass fit for the sample identified by a tau leptons decaying into ρ. Here we generated 10,000 $\tilde{\tau}$ pairs with mass $m_{\tilde{\tau}_1} = 150$ GeV which decayed into $\chi\tau$ with $m_\chi = 100$ GeV. We also included backgrounds consistent with $\int L = 100 fb^{-1}$. About 1700 events of ρ are obtained for the signal after the cut, while 93 events remained as the backgrounds. Contours of constant $\chi^2 = -1/2\log L$ are shown in Fig. 1. We show the result in the m_χ and $m_{\tilde{\tau}_1}$ plane fixing the other parameters [**)]. $m_{\tilde{\tau}_1}$ is determined with the error of 3.5 GeV. The error of the cross section at the best fit point is 2.5%.

The errors corresponding to 5000 events are shown in fig. 2 schematically in

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*) For Monte Carlo simulation, we used TAUORA ver2.4 [13]. See next subsection to our cuts to identify ρ and a_1.

**) The results are obtained by normalizing the total number of the events of the fitting curve of the signal and background by the event number obtained by MC. $P_\tau = 1$ both for MC and the theoretical distribution. The determination of P_τ is discussed in the next subsection

$m_{\tilde{\tau}_1}$ and $\sin\theta_\tau$ plane(scaled statistically), where the contours of constant $\sigma_{\tilde{\tau}_1}$(=50fb dotted line, $50 \pm 1.25 fb$ solid lines) are shown simultaneously. $\delta\theta_\tau = \pm 4.5^\circ$ is read from the figure.

We showed the measurement of the $\tilde{\tau}_1$ production and decay can determine two of the three parameters of $\tilde{\tau}$ mass matrix. Discovery of $\tilde{\tau}_2$ would specify the remaining degree of freedom.

2.3. *The Yukawa sector of MSSM and P_τ*

The study of $\tilde{\tau}$ may play important role in exploring the Yukawa sector of MSSM [8]. Let's consider the decay of $\tilde{\tau}_1 \to \tau\chi^0_1$ again. The χ^0_1 is the mixture of gauginos ($\tilde{B}, \tilde{W}$) and Higgsinos ($\tilde{H}_{1(2)}$). The interaction involving gaugino component ($\tilde{B}(\tilde{W})$-τ-$\tilde{\tau}$ coupling) is proportional to gauge couplings and the interaction involving Higgsino component ($\tilde{H}_1$-τ-$\tilde{\tau}$ coupling) is proportional to τ Yukawa coupling $Y_\tau \sim m_\tau/\cos\beta$. The latter may not be too small compared to the former when $\tan\beta$ is large or χ^0_1 has the large higgsino component(See Fig. 3).

Those two interactions are different not only in the couplings, but also in the chirality of the (s)fermion. The (super-) gauge interaction is chirality conserving, while the (super-) Yukawa interaction flips it. (In Fig.3, the arrows next to the $\tilde{\tau}$ and τ lines show the direction of chirality.) Thus the polarization of τ lepton (P_τ) from $\tilde{\tau}_1$ decays depends on the ratio of the chirality flipping and concerning interactions.

$P_\tau(\tilde{\tau}_1 \to \tau\chi^0_1)$ depends on $\tan\beta$ strongly compared to other quantities. To demonstrate this, we show various quantities in Fig.4 a)-d) fixing $m_{\chi^0_1} = 100$ GeV and varying M_1($\tilde{B}$ mass parameter) and $\tan\beta$. Fig.4 a)-c) show little dependence on $\tan\beta$. Especially the pair production of $\tilde{e}_R$ can be used as the mode to determine M_1 as in Ref.6). On the other hand, $P(\tilde{\tau}_R \to \tau\chi^0_1)$ depends on $\tan\beta$ sensitively if M_1 is sufficiently larger than $m_{\chi^0_1}$ or $\tan\beta$ is large. This is because the chirality flipping higgsino interaction becomes comparable to the chirality conserving gaugino interaction either if the lightest neutralino is dominantly Higgsino or if Y_τ is large [*]. In such a situation, one can determine $\tan\beta$ by using the value of M_1 obtained by the other production processes.[**]

The measurement of P_τ would be carried out through the energy distribution of decay products from the polarized τ lepton. The τ lepton decays into $A\nu_\tau$ where $A = e, \mu, \pi, \rho, a_1 ...$ For the each decay channel, the momentum distribution of the hadronic decay products ($\pi^\pm$, $\rho^\pm \to \pi^\pm\pi^0 ...$) differs significantly depending on P_τ. If the τ lepton is relativistic, P_τ can be determined from the energy distribution of the decay products [15].

Being more specific, let us consider the decay of a polarized τ lepton into ρ. The ρ from right(left) handed τ lepton is longitudinally(transversally) polarized. The ρ meson then decays into $\pi^\pm\pi^0 \to \pi^\pm 2\gamma$. The energy fraction $E_{\pi^\pm}/E_\rho$, where E_ρ is

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*) The neutralino sector is parametrized by $M_{1(2)}$, μ, $\tan\beta$. When $\mu \ll (\gg) M_1$, χ^0_1 is dominantly higgsino(gaugino) and $m_\chi \sim \mu(M_1)$. In Fig.4, χ^0_1 becomes dominantly higgsino as M_1 becomes larger.

**) One can also determine $\tan\beta$ from forward-backward asymmetry of chargino production cross section. It is sensitive to $\tan\beta$ when $M_2 \sim \mu$ [14), 7)]

the total energy of jets which the $\pi^\pm$ belongs to, depends on ρ polarization in a very simple form in the collinear limit($E_\tau \gg m_\tau$);

$$\frac{d\Gamma(\rho_T \to 2\pi)}{dz} \sim 2z(1-z) - \frac{2m_\pi^2}{m_\rho^2}, \quad \frac{d\Gamma(\rho_L \to 2\pi)}{dz} \sim (2z-1)^2, \tag{2}$$

where $z = E_\pi/E_\rho$.

Notice that decay of the τ lepton into the heavier meson a_1 may be misidentified as decay into ρ if the energy and momentum resolution of the detector is poor. The decay $\rho \to \pi^+ 2\gamma$ will be identified as a jet of a π^+ and one or two photon candidates. On the other hand, the decay $a_1^\pm \to \pi^\pm\pi^0\pi^0 \to \pi^\pm 4\gamma$ is also occasionally misidentified as $\pi^\pm 2\gamma$ or $\pi^\pm\gamma$ which contaminates ρ signals. We applied the cuts $m_j < 0.95$ GeV for events with one photon candidate and $m_j < 0.95$ GeV and $m_{2\gamma} < 0.25$ GeV for events with two photon candidates to reduce the contamination from a_1 decay; after the cut the contamination is less than a few % for $m_{\tilde{\tau}_1} = 150$ GeV $m_\chi = 100$ GeV. However, the purity of the sample crucially depends on the assumed performance of the JLC 1 detector [4]. If this is not achieved, one may have to look up the decay mode into $\tau^\pm \to \pi^\pm\nu$ or $a_1^\pm \to \pi^\pm\pi^\pm\pi^\mp$. The branching ratio into those modes are small compared to the one into ρ.

Fig.5. shows the z distribution of MC events and the fit for the same parameter with Fig 1. The best fit value of P_τ is $0.95(-0.92)$ for $P_\tau = 1(-1)$ respectively and the estimated error is ± 0.07 [*]

§3. Conclusion

I presented in this talk our study of the production and decay of the lighter scaler tau lepton $\tilde{\tau}_1$ at a future LC. The study of $\tilde{\tau}$ is important because $\tilde{\tau}$ may be lighter than the other sleptons, thus would be found earlier. The light $\tilde{\tau}_1$ is well motivated in MSUGRA-GUT model, and it is not excluded in other models, if there is large $\tilde{\tau}_L$-$\tilde{\tau}_R$ mixing.

We discussed that the mass matrix of $\tilde{\tau}$ provides a clue to distinguish SUGRA-GUT model and DNNS model, and the polarization of τ lepton P_τ from decaying $\tilde{\tau}_1$ is sensitive to the value of $\tan\beta$ through its dependence to the τ Yukawa coupling; $\tan\beta$ is one of the important parameters to determine the Higgs sector of the MSSM.

The feasibility of the study of those parameters at the LC have been checked by MC. The error of $m_{\tilde{\tau}_1}$ and $\sigma(\tilde{\tau}_1\tilde{\tau}_1)$ (which in turn used to determine the mass matrix of $\tilde{\tau}_1$) and P_τ are 3.5 GeV, 2.5 % and 0.07 respectively for a representative parameters we have chosen. We have not included several potentially important background such as $\gamma\gamma \to \tau\tau$ and production and decay of heavier superpartners. However, we believe final results will not be too much different to the ones we have presented here.

In near future, LEPII and LHC are scheduled to operate at $\sqrt{s} = 180$ GeV and $\sqrt{s} = 14$ TeV respectively. However, their ability to determine the soft breaking

[*] For the analysis we took the event where $0.08 < z < 0.92$ to avoid detector effects. We used the events $E_j > 20$ GeV as the events below the cut does not have the sensitivity to P_τ

mass parameters is rather poor. For LEPII, integrated luminosity is $\mathcal{O}(100pb^{-1})$, while the production cross sections are typically $\mathcal{O}$(10pb) for chargino and 0.3 pb for $\tilde{\mu}$ with $m_{\tilde{\mu}} = 60$ GeV. The production cross section of a slepton is too small to go beyond discovery physics. Feng and Strasslar showed that precise study of chargino interactions is possible [14], however, one has to still fight over the enormous background coming from W^+W^- production. SUSY study at LHC(Large Hadron Collider) suffers from the high QCD background although strongly interacting superpartners will be copiously produced at LHC. Expected signals of SUSY particle production are also very complicated, as decay patterns of squarks and gluino change drastically depending on the mass spectrum of SUSY particles.

Implications of MSUGRA model at LEPII and LHC have been discussed and studied in quite a few papers. Those are mostly about the reduction of the number of free parameters of the model (which tighten the phenomenological constraint), "theoretical upper bound" of sparticle masses, and (therefore) when and how they would be discovered. However, it is becoming recognized that we can go beyond that if a next generation LC is actually built. Namely, the experiment at the LC will make it possible to measure the parameters of MSSM once a superpartner is discovered, and this enablesy us to check the predictions of the models of SUSY breaking. I presented in this talk that discovery of $\tilde{\tau}$ at the LC provides us a clear cut to understand the origin of SUSY breaking, and I hope I have convinced the audiences that the LC is necessary to achieve that.

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